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Multimode Lasing at Room Temperature from InGaAs/GaAs Quantum Dot Lasers

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We demonstrate InGaAs/GaAs quantum dot lasers with multimode lasing at room temperature immediately above threshold. The lasing modes are separated by about ten times the Fabry-Perot mode spacing, with several dark modes in between the lasing modes. Rate equation simulations indicate that this multimode behavior can be explained by a homogeneous broadening that is on the order of the mode spacing.

Introduction and Background

It has been generally observed [1,2] that semiconductor lasers with InAs/InGaAs quantum dot (QD) active regions operated at room temperature exhibit single-mode lasing for current injection significantly above threshold. This behavior is consistent with the lasing characteristics of a homogeneously broadened gain medium [3]. Direct measurements of the homogeneous broadening of InAs/InGaAs QD optical transitions by Borri *et al.* [4] yielded a homogeneous broadening of approximately 19 meV at room temperature for high electrical injection levels. This number represents a significant fraction of the inhomogeneous broadening (30-60 meV), and therefore it is not surprising that InAs/InGaAs QDs behave as a homogeneously broadened medium. At low temperatures, on the other hand, multimode lasing from QD lasers is generally observed [1,5]. This points to the fact that the homogeneous broadening of the quantum dots increases with temperature, most likely due to increased carrier-phonon scattering.

In contrast to the results referenced above, we have observed multimode lasing at room temperature from our InGaAs/GaAs quantum dots. In this paper, we will present this data, as well as simulations that confirm that the room temperature homogeneous broadening is small (~ 1 meV) in our quantum dots. We will present physical explanations for the narrow homogeneous broadening we observe. Finally, we will present an application for these quantum dots as an active region for a semiconductor optical amplifier (SOA).

Experimental Results

The active region of our lasers consisted of three layers of InGaAs/GaAs quantum dots inside a 1.7 mm long cavity. The lasers were operated at room temperature and were electrically pumped with 0.8 μsec pulses at a 1 kHz repetition rate. The threshold current density was 1.3 kA/cm^2, which is much higher than the best room temperature threshold current densities reported by other groups, e.g. 26 A/cm^2 [6].

The optical output power for a typical device is plotted as a function of wavelength in Fig. 1 at a current injection level 1.1 times threshold. Several modes are lasing at this bias. The three central modes are separated by roughly 1 nm, which is about 10 times greater than the Fabry-Perot optical mode spacing of 0.1 nm. Thus, there are about 10 non-lasing modes in between each lasing mode in the central grouping. There is a fourth mode separated from the central mode grouping by a much greater spacing. This large spacing is most likely due to reflections from the bottom of the substrate [7] and is not of interest to us here.

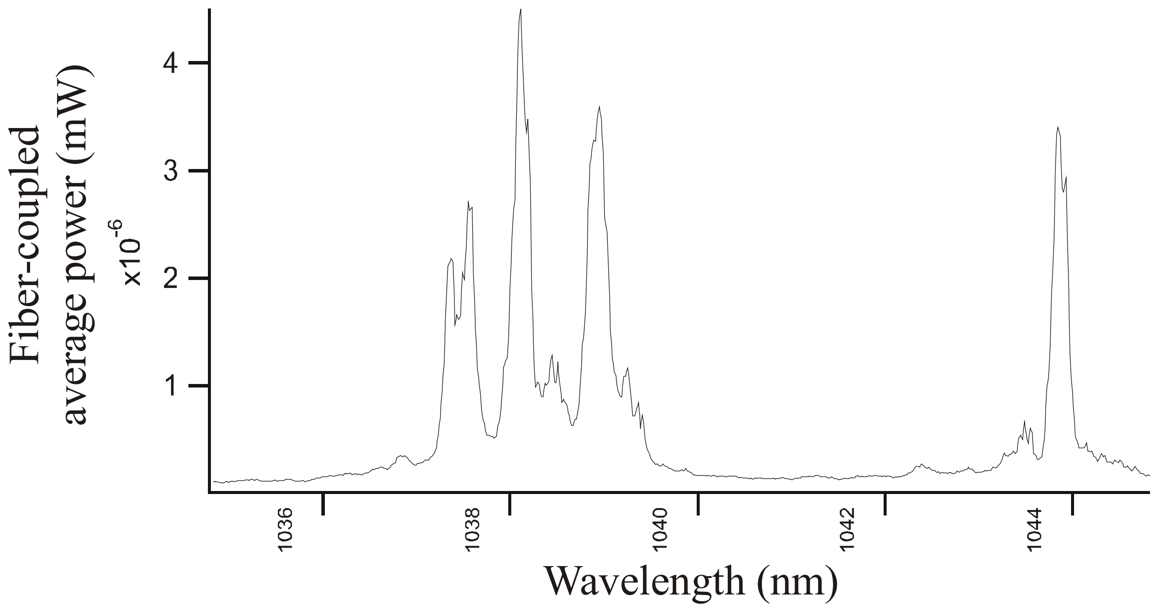

Fig. 1. Output optical power vs. wavelength at 1.1 x threshold.

The lasing mode spacing of 1 nm (1 meV) suggests that the homogeneous width of the optical transitions in these dots is approximately 1 meV. Intuitively, only a single mode will be able to lase within the homogeneous width (barring spatial hole burning): the lasing mode will stimulate all of the recombination within that width, and reap all of the resulting photons. The effort of the next section will be to prove that the homogeneous width must be on the order of 1 meV.

Simulations of Lasing

Simulations of the QD laser are carried out to determine more precisely the dependence of the lasing spectrum on the homogeneous width. The simulations are based on a rate equation model of the laser. The rate equations employed are similar to those used in Ref. 8. Coupled rate equations represent the carrier populations of the separate confinement heterostructure (SCH), the wetting layer (WL), and the quantum dots (QDs), as well as the photon populations of the Fabry-Perot optical modes. The distribution of quantum dot energy gaps (due to the nonuniformity of quantum dot sizes) is taken to be Gaussian with a FWHM of 30 meV, obtained from photoluminescence measurements of our dots. This inhomogeneous broadening is handled in the simulator by dividing the entire collection of quantum dots into many groups or "bins," each containing all of the dots within a small energy range (~ 60 μeV). Every quantum dot within a bin is assumed to have the same fractional population as all of the other dots within that bin. The rate equations are written as

$$\frac{dN_{SCH}}{dt} = \frac{I}{e} - \frac{N_{SCH}}{\tau_{SCH}} \tag{1}$$

$$\frac{dN_{WL}}{dt} = \frac{N_{SCH}}{\tau_{SCH}} + \sum_{QDs} \frac{N_{QD}}{\tau_{esc}} - \frac{N_{WL}}{\overline{\tau}_{cap}} - \frac{N_{WL}}{\tau_{recom}} \tag{2}$$

$$\frac{dN_{QD}}{dt} = \frac{N_{WL}}{\tau_{cap}} - \frac{N_{QD}}{\tau_{esc}} - \frac{N_{QD}}{\tau_{recom}} - \sum_{modes} g_{QD,mode} S_{mode} \tag{3}$$

$$\frac{dS_{mode}}{dt} = R_{spon} - \frac{S_{mode}}{\tau_{phot}} + \sum_{QDs} g_{QD,mode} S_{mode} \tag{4}$$

where N is the carrier number (electron and hole concentrations are assumed to be equal), I is the current injected into the device, S is the photon number, and R_{spon} is the spontaneous emission into each mode. The capture and escape times (τ) are as follows: τ_{SCH} is the capture time from the separate confinement heterostructure into the wetting layer, τ_{esc} is the escape time from a quantum dot into the wetting layer, τ_{cap} is the capture time from the wetting layer into a quantum dot bin (τbar$_{cap}$ is the capture time into all of the dot bins), and τ_{recom} is the recombination time of carriers in the wetting layer or a QD due to dark recombination and spontaneous emission. The two times of greatest importance here are τ_{esc}, which was taken to be 10 ps, and τ_{cap}, which depends inversely on both the number of dots and one minus the fractional occupation of the dots. The empty dot value of τ_{cap} was taken to be 10 ps. These values were gathered from values quoted in the literature and our own experimental results. The term of particular interest here is the stimulated recombination term $g_{QD,\ mode}$, which contains the homogeneous broadening as

$$g_{QD,mode} \propto N_{dots}(2f_{dot} - 1)\int_{bin} dE'\, B(E_{mode} - E') \tag{5}$$

where N_{dots} is the number of QDs in the dot bin, f_{dot} is the fractional occupation of the dots in the dot bin, E_{mode} is the center energy of the optical mode, and B is the homogeneous broadening function, here taken to be Lorentzian. The broadening function is integrated over the width of the dot energy bin, in order to obtain the contribution of the dots in that bin to the gain of a given mode. After all of the terms are calculated, the set of rate equations is solved on a computer using Newton's method. In the simulations presented here, the FWHM of the homogeneous broadening function was varied and the resulting lasing spectrum recorded.

Figure 2 shows the L-I curve for a laser simulation with a homogeneous broadening of 5 meV. The device exhibits single mode lasing for bias currents far above 1.1 times threshold. The output power plotted as a function of wavelength for 1.1 times threshold would exhibit a single lasing mode. Clearly the broadening in the experimental device is less than 5 meV.

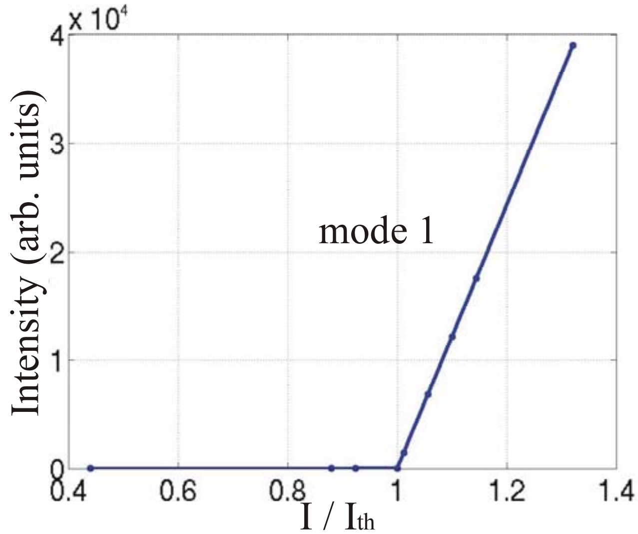

Fig. 2. Calculated L-I curve for homogeneous broadening FWHM of 5 meV.

Figure 3 shows the intensity spectrum vs. wavelength for a homogeneous broadening of 1 meV. Here we see behavior that closely corresponds to the experimental case: three lasing modes grouped together, separated by approximately 1 nm, with ten dark modes in between.

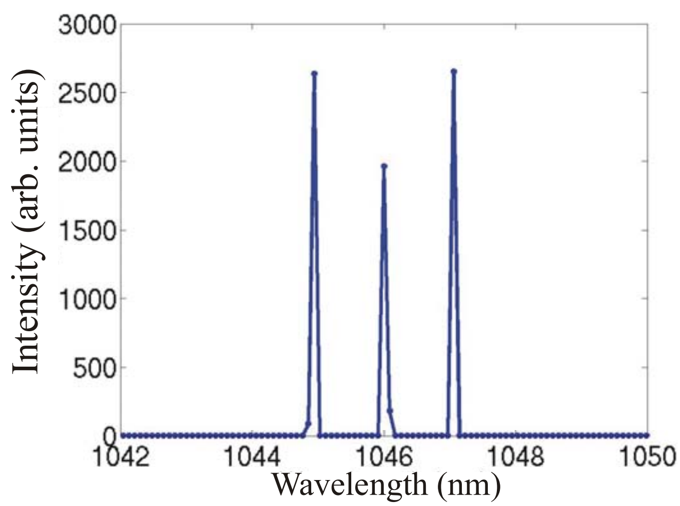

Fig. 3. Calculated output optical intensity vs. wavelength at $I = 1.1 \times I_{th}$ for homogeneous broadening FWHM of 1 meV.

Our simulations also indicate that a QD laser with a homogeneous broadening less than 0.5 meV operating at 1.1 times threshold exhibits more lasing modes separated by fewer dark modes than seen in the experiment. Thus, our experiment and the simulations provide indirect but compelling evidence that the homogeneous broadening of our dots is approximately 1 meV. The reason that the homogeneous broadening of our dots at room temperature is significantly smaller than that reported by other groups is most likely the difference in material compositions. The dots we use are InGaAs capped with pure

GaAs, whereas it is common for most groups to incorporate In into their GaAs cap in order to enhance electroluminescence. We therefore arrive at a consistent explanation for the observed facts of higher threshold current densities and narrower homogeneous broadening: our dots are more isolated from the surrounding media and one another. The carriers are therefore less likely to couple into the dots, and carriers bound in the dots are more localized in real space. This in turn leads to greater localization in energy space, as the capture and emission processes that couple the populations of different dots are slow, and scattering processes that broaden optical transitions are reduced. Above threshold, the fast stimulated recombination overwhelms the slow carrier capture and emission processes. Thus there is no Fermi level shared amongst all of the dots above threshold.

The use of these spectrally and spatially isolated quantum dots for laser applications is hampered by the necessarily large transparency and threshold current densities that they require. The next section will present a possible application for these dots in SOAs.

Simulations of Semiconductor Optical Amplifier Operation

A common problem with quantum well (QW) semiconductor optical amplifiers used in wavelength division multiplexed (WDM) systems is cross-gain modulation. This problem may be briefly summarized as follows: if two or more signal channels at different wavelengths are injected into the device for amplification, the gain given to one channel will reduce the gain available for the other channels, and vice versa. This is due to two interrelated effects: the wide homogeneous broadening of QW optical transitions and fast carrier redistribution in energy space. Thus, this problem can be addressed by replacing the QW active medium with an active medium consisting of spectrally isolated InGaAs/GaAs quantum dots [9,10].

Simulations of a QDSOA have been carried out using the same rate equations (1) – (3), with the exception of the photon rate equation (4). The photon number here is treated as an input. The simulations were carried out assuming a channel spacing of 20 nm, which is typical of coarse WDM. The gain spectrum is taken to be centered around 1 μm, which is consistent with the observed photoluminescence spectrum of our quantum dots.

Figure 4 shows the calculated gain vs. time for two coarse WDM channels in a QDSOA, with a 20 ps light pulse injected into the channel at 1056 nm. The intensity of the light pulse was chosen such that the gain of the 1056 nm channel in the 1 meV broadening case was reduced by approximately 50%. The time dependence of the gain during the duration of the light pulse (0 – 20 ps) can be roughly split into two parts. The first part is an abrupt drop in the gain, which is due to stimulated carrier recombination in the quantum dots situated within several homogeneous widths of the light pulse's center frequency. The second part is a much slower decrease in the gain, which is due to the reduction of the total carrier population of the wetting layer and all of the dots. The slow decrease is rate-limited by the capture and emission processes which allow communication amongst the dots and the wetting layer.

Widening the homogeneous broadening affects both the fast and the slow processes described above. A wide homogeneous broadening distributes the effect of the fast gain decrease more evenly across the spectrum of dots. In addition, widening the homogeneous broadening increases the effect of the slow gain decrease across the entire spectrum: the total carrier population is decreased by a larger amount, as the aggregate of carriers has more parallel paths leading to stimulated recombination. In Fig. 4 the gain for each channel is plotted for the cases of (a) 1 meV broadening and (b) 10 meV broadening. As can be seen, for 1 meV broadening the gain for the second (dark) channel is essentially unaffected, whereas for 10 meV broadening the gain for the second channel is reduced by roughly 10%.

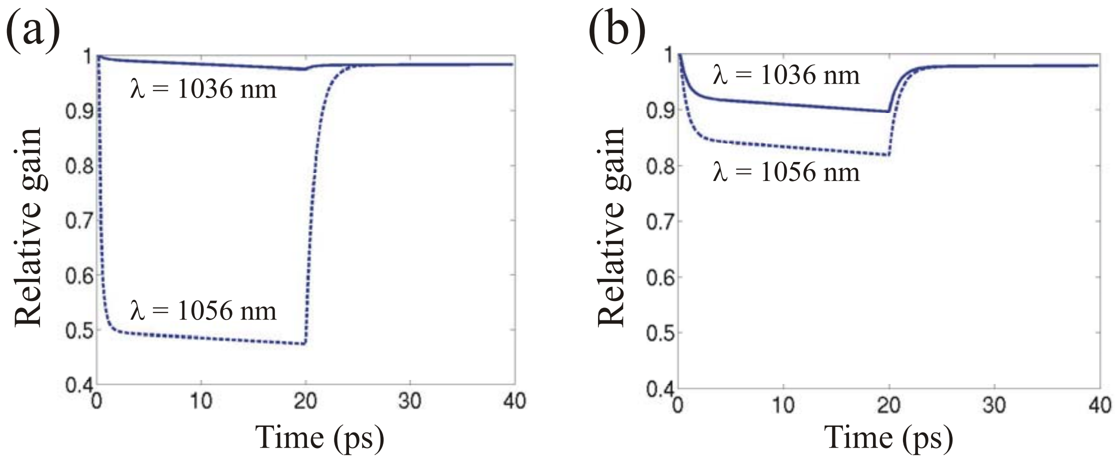

Fig. 4. Calculated relative gain vs. time for 20 ps light pulse injected into QDSOA at 1056 nm. Homogeneous broadening FWHM of (a) 1 meV and (b) 10 meV. The optical intensity of the pulse is the same for both cases.

Fig. 5 shows the relative gain plotted against wavelength for the narrow and the wide broadenings, at t = 20 ps (t = 0 ps is included for reference). In the case of the 1 meV broadening, the optical pulse at 1056 nm burns a spectral hole in the gain while leaving most of the gain spectrum relatively unchanged. In the case of the 10 meV broadening, the entire gain spectrum is pulled down by the pulse at 1056 nm.

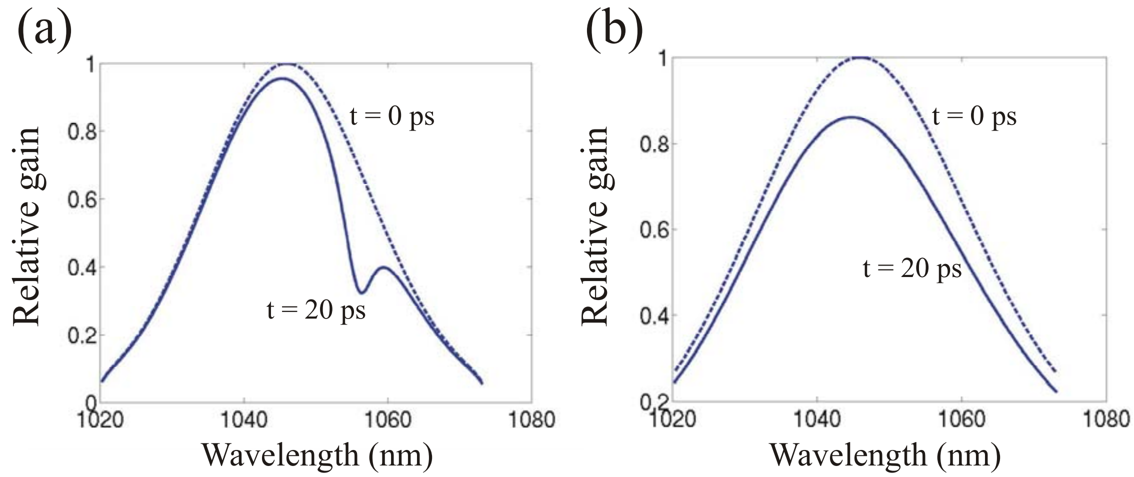

Fig. 5. Calculated relative gain vs. wavelength for 200 ps light pulse injected into QDSOA at 1056 nm. Homogeneous broadening FWHM of (a) 1 meV and (b) 10 meV.

Conclusions

In contrast to the results obtained by most experimental groups, we have observed multimode lasing at room temperature from our InGaAs/GaAs QDs. This behavior is characteristic of an inhomogeneously broadened medium. In essence, these results offer a useful design option for QD optical device engineers. With wide homogeneous broadening, which may be obtained by manipulating the material contrast between the cap and the dots, low threshold current densities and single mode lasing may be obtained. With narrow homogeneous broadening, higher threshold current densities and multimode lasing may be obtained. Narrow homogeneous broadening additionally leads to a reduction of cross-gain modulation in a QDSOA. A better understanding of the lasing properties of various QD material systems will lead to improved device performance for specific applications.

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